in FDMA/TDMA systems, or code channels as in CDMA systems. Other transmitters actively transmitting in the same channel at the same time are considered to be *cochannel interference*, a situation which current systems attempt to prevent since it leads to significant performance degradation. Cochannel interference, in fact, is a major factor in determining how often (spatially) frequency channels can be reused, *i.e.*, assigned to different cells. The cochannel interference problem pervades all wireless communication systems, not just cellular mobile communications, and attempts to solve it in current systems have all been formulated on the premise that the cochannel signals represent disturbances to be eliminated and that only one antenna/receiver output is available for the task.

2.4 Time-domain Equalization

Time-domain adaptive filter techniques have been developed to improve channel quality for digital transmission in the presence of Rayleigh fading which causes intersymbol interference at the receiver. Such *equalization* techniques have been adopted in the current digital GSM and IS-54 cellular systems (D. Goodman, "Trends in Cellular and Cordless Communications," *IEEE Communications Magazine*, June 1991). These techniques are completely compatible with SDMA and can be incorporated in the demodulation step as is currently done in practice. In fact, in many environments characterized by a small number of specular reflections, the equalization problem can be substantially mitigated by appropriately combining the multipath signals arriving from different directions in a process very similar in nature to the concept of *rake filtering* in the time domain.

2.5 Exploiting the Spatial Dimension

The undesirable characteristics of the aforementioned adaptive techniques are a consequence of the fact that only assumed time-domain properties of the received signals are being exploited, and that one of the signals present in the data is treated differently than the remaining signals, *i.e.*, the cochannel interferers. The philosophy adhered to which is unique to SDMA is that cochannel interferers simply represent a plurality of users attempting to access the system simultaneously on the same channel. The fact that SDMA can handle this situation regardless of the modulation type (analog or digital) and in the presence of multiple arrivals of the same signal (*i.e.*, *specular multipath*) is a distinguishing feature over current systems.

Efficient exploitation of the spatial dimension to increase capacity requires the ability to separate a number of users simultaneously communicating on the same channel at the same time in the same local area. This separation is performed as discussed in detail in the next section by distinguishing the signals on the basis of their angle-of-arrival, information which is used to ascertain the location of the mobile transmitters. The process of localization of the mobile transmitters is another distinguishing feature of SDMA over current systems.

Possibly due to the heretofore complex nature of systems containing multiple sensors, wireless communication network designers have eschewed multiple antenna/receiver systems in favor of the simpler single (omnidirectional) receiver. However, with the advent of high-speed general purpose digital signal processors, these complex algorithms are capable of being performed in real-time, making the use of state-of-the-art signal parameter estimation algorithms viable for real-time multiple signal location estimation and cochannel signal separation. Unique to SDMA is the application of these techniques to real-time multiple cochannel source location estimation for improving the capacity and quality of wireless communication networks and, in particular, to PCSs.

3. Detailed Description of SDMA

In this section, a brief overview of current FDMA/TDMA wireless communications systems is presented. Then details of the SDMA system are discussed. Results obtained in processing simulated and real data are presented indicating the efficacy of SDMA in the PCS environment.

3.1 Brief Description of Current Systems

FIG. 3-1 shows the current state-of-the-art in wireless communication networks. Wireless transmitter/receiver units (20,22,24) are assigned to distinct (frequency) channels and thereby allowed to communicate simultaneously. As aforementioned, these *channels* can be frequency channels, time-slots in particular frequency channels, or code channels in a particular frequency channel. A multi-channel receiver (26) exploits the fact that they are on different frequency channels to correctly separate the signals (28,30,32) which are then subsequently demodulated and passed along to the rest of the network. A multi-channel transmitter (40) transmits signals (34,36,38) to the wireless units (20,22,24) in another set of distinct frequencies. For example, in current cellular mobile communication systems, mobile units receive transmissions from base stations in channels 45 MHz above those frequency channels they transmit information to the base stations. This allows for simultaneous transmission and reception of information at both the base station and mobile units. It is also possible to use time-multiplexing and voice compression to transmit and receive on the same frequency, however this concept would not be amenable to high-speed continuous data transmission.

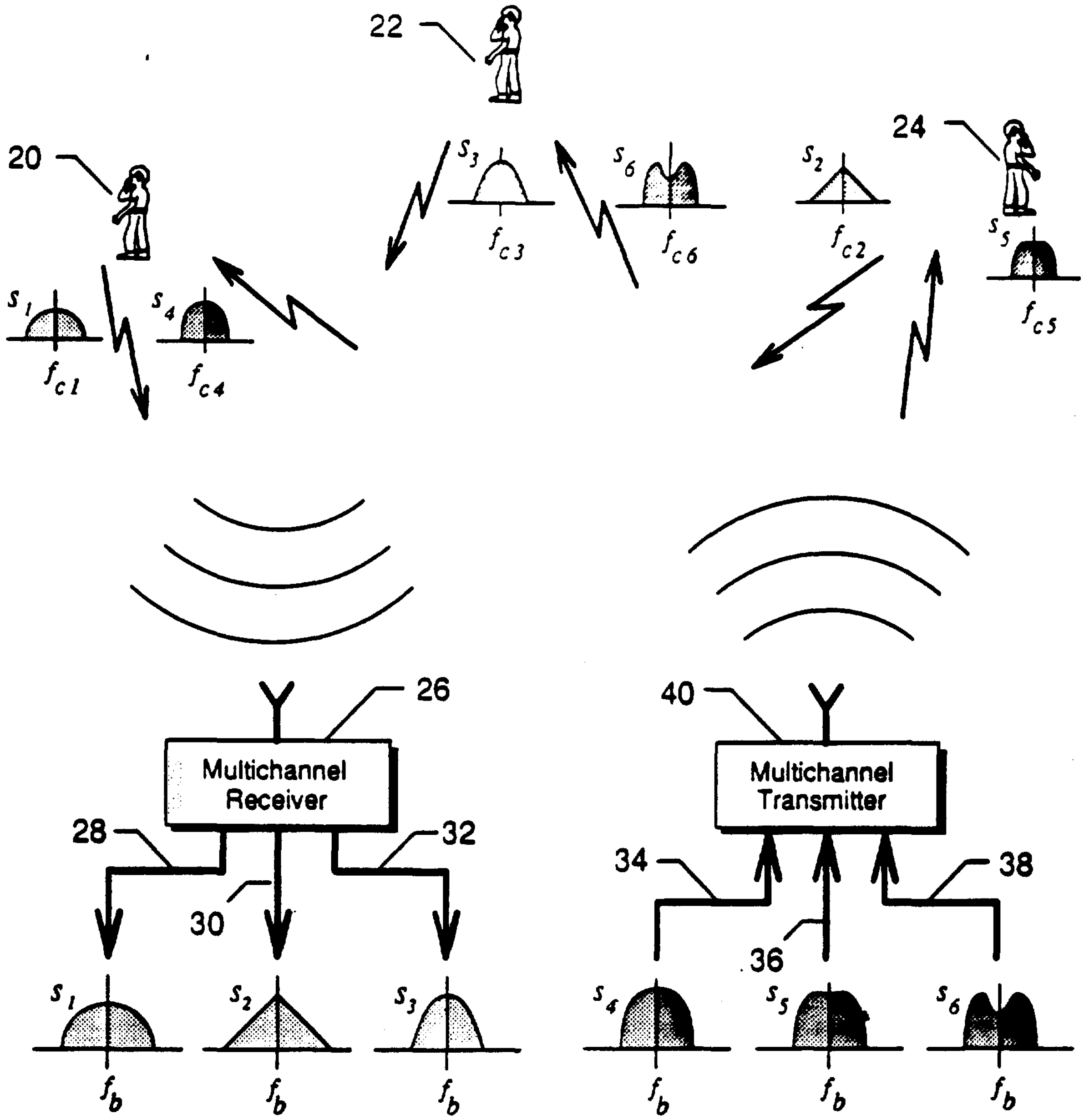

Figure 3-1: Diagram of Current FDMA Systems: Multiple Wireless Units Transmitting on Different Channels at the Same Time

3.1.1 Cochannel Interference and System Limitations

FIG. 3-2 shows a limitation of current wireless communication systems. Wireless units (20,22,24) transmitting on the same conventional channel (the same carrier frequency f_{c1} in this diagram) can not be resolved at the receiver (26) due to the fact that there is no way to distinguish one signal from the other when they share the same channel. The receiver output (28) is a combination of *all* signals present in the channel even after down-conversion to baseband frequency f_b.

FIG. 3-3 shows a similar limitation of current wireless communication systems with respect to communication from the base station transmitter (40) to the remote receivers. The function of the multi-channel transmitter is to up-convert signals from baseband frequency f_b to one of the multi-channel carrier frequencies for transmission to the mobile unit. Wireless units (20,22,24) on a particular channel (the same carrier frequency f_{c1} in this diagram) receive a combination of multiple signals transmitted from the base station transmitter (40) in that frequency channel (34). This is due to the fact that there is no method in the current state-of-the-art for preventing all signals transmitted in the same frequency channel from reaching all receivers in a given cell or sector thereof set to receive signals in that particular channel. Signals received at the wireless units are combinations of all signals transmitted in that channel.

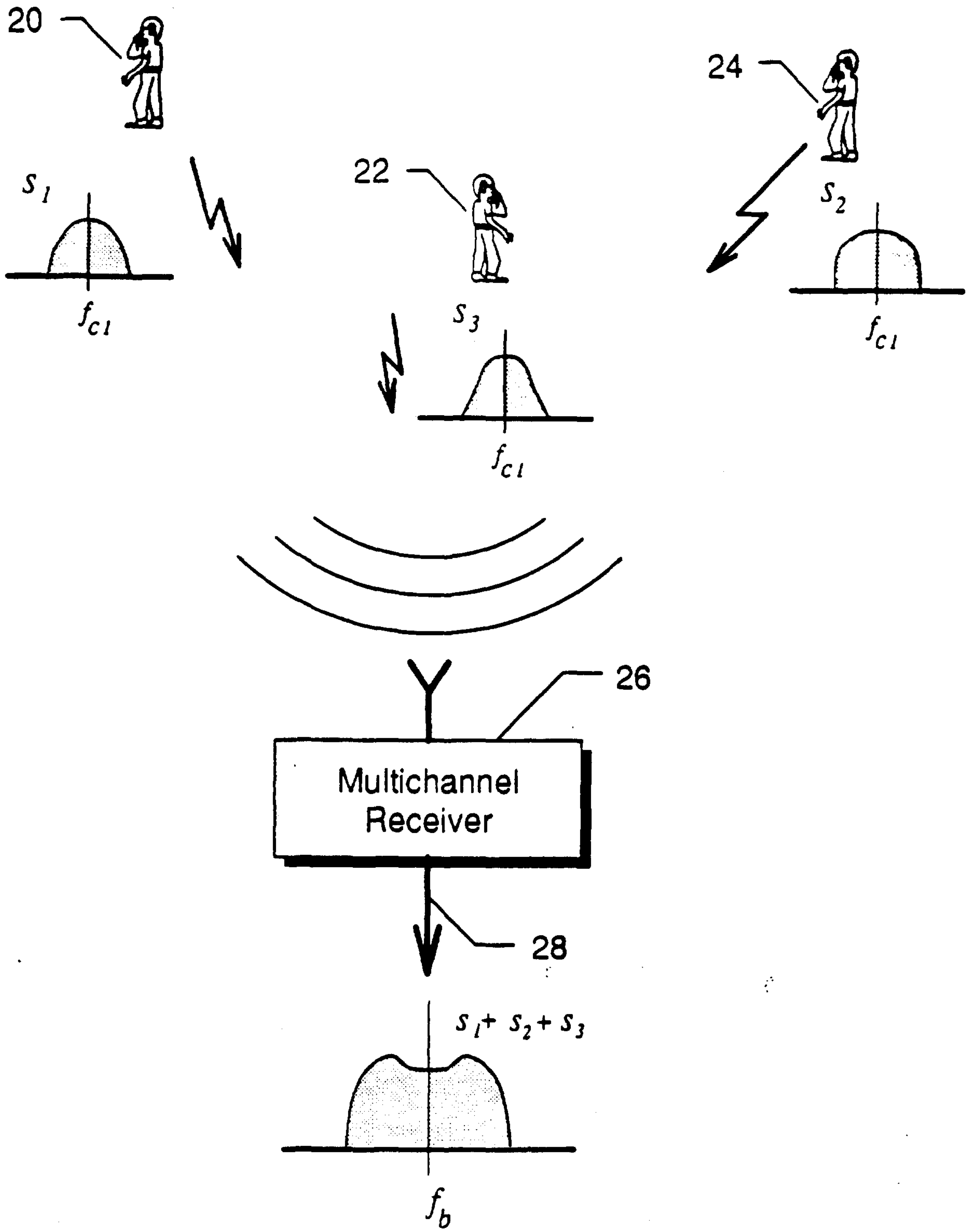

Figure 3-2: Cochannel Interference Resulting from Multiple Wireless Units Transmitting on the Same Channel at the Same Time

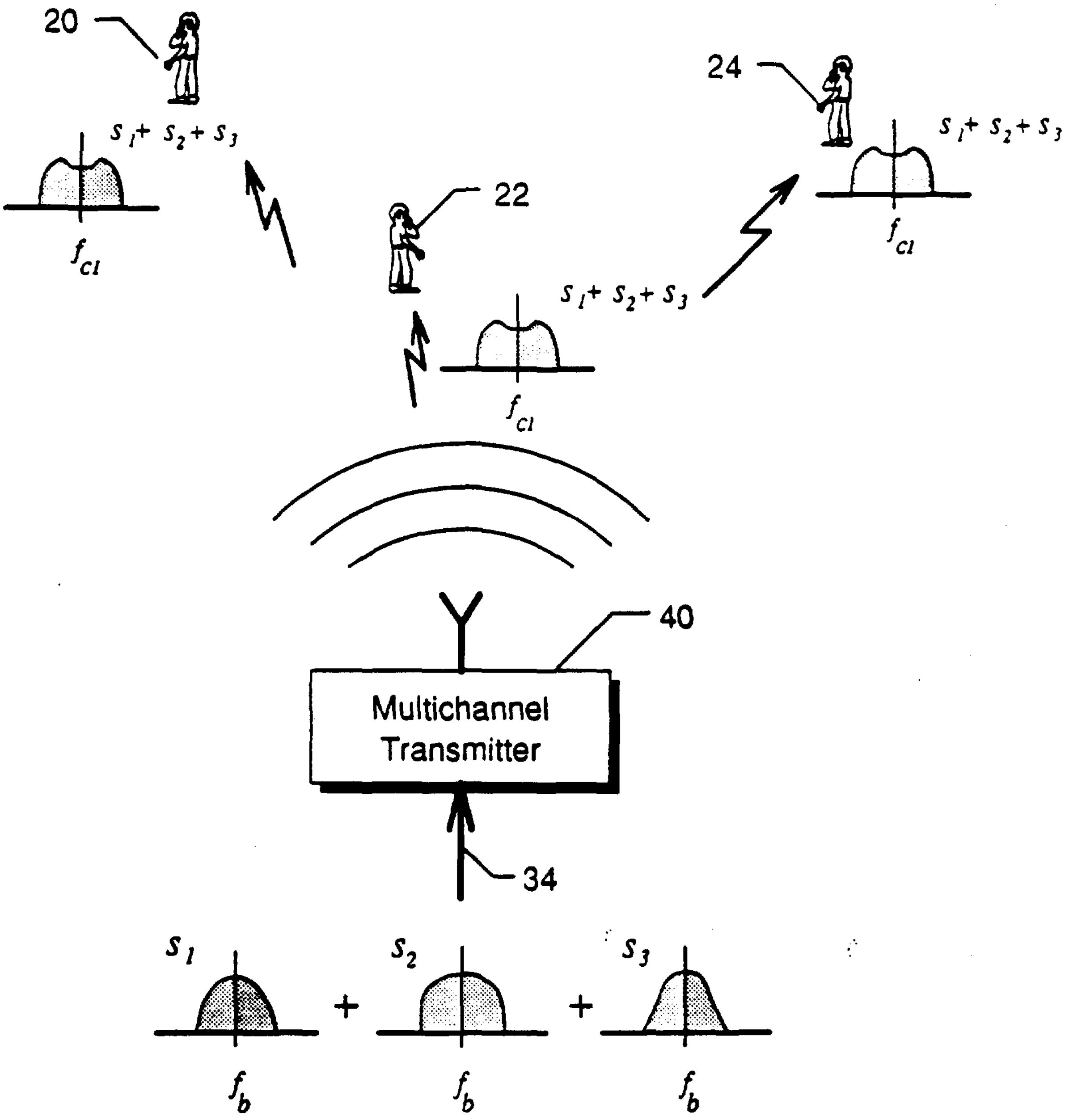

Figure 3-3: Cochannel Interference Resulting from Broadcast Transmission of Multiple Signals on the Same Channel to Multiple Wireless Units at the Same Time

3.2 SDMA

3.2.1 Spatial Demultiplexing for Reception

FIG. 3-4 is an illustration of how SDMA overcomes the aforementioned multiple signal reception problem at one or more base stations. Multiple signals from wireless units (20,22,24) transmitting in the same channel are received by an array of sensors and receivers (42). These *cochannel* signals are spatially demultiplexed by a spatial demultiplexer (46) which is controlled by a Spatial Division Multiple Access signal Processor (SDMAP) (48). The demultiplexed signals (50) are then sent to signal demodulators as is done in current systems.

3.2.2 Spatial Multiplexing for Transmission

FIG. 3-5 is an illustration of how SDMA overcomes the aforementioned multiple signal reception problem at the mobile wireless unit. Multiple signals (64) from signal modulators, assumed therein as all being in the same frequency channel for illustrative purposes, are appropriately combined by a spatial multiplexer (66) under control of the SDMAP (48) so as to eliminate all cochannel interference at the wireless units (20,22,24). These signals (68) are sent to multichannel transmitters (70) and subsequently transmitted by an array of antennas to wireless units (20,22,24). As indicated in the illustration, by appropriate design of the spatial multiplexer using Spatial Communications, Inc. proprietary algorithms, wireless unit (20) receives none of the signal being transmitted to units (22) or (24), and similarly for the other two units. In conjunction with FIG. 3-4, multiple full-duplex links are hereby established.

FIG. 3-6 shows a block diagram of an SDMA system successfully receiving multiple signals in one channel and transmitting multiple signals in another channel by using different spatial channels. The intent of the figure is to indicate that these messages are broadcast on the same (frequency) channels, from the wireless units to the base-station at f_{c1} and from the base station to the wireless units at f_{c2}, at the same time. This is a situation heretofore not allowed in current FDMA and TDMA systems since the messages *interfere* with each other as indicated in FIG. 3-2 and FIG. 3-3. Signals transmitted in the same channel by wireless units (20,22,24) are received at the base station by multiple antennas. The output of each of m_r antennas is sent to a *multichannel receiver* as is currently done in single antenna systems.

3.2.3 Description of the SDMA System

The multichannel receiver takes an antenna input and has one output for each frequency channel which it is capable of processing. For example, in proposed PCS systems,

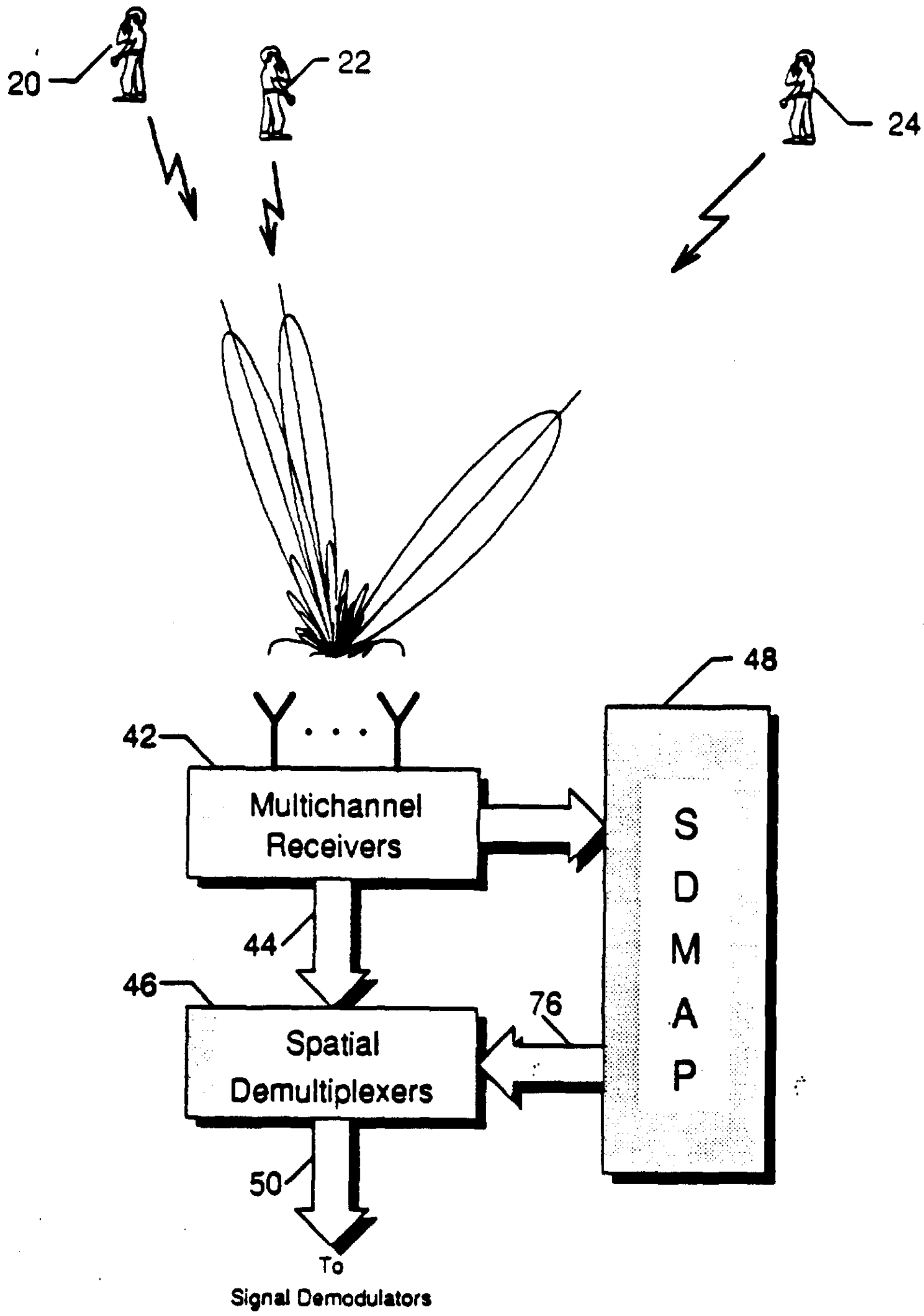

Figure 3-4: Multiple Cochannel Signal Reception at the Base Station Using SDMA

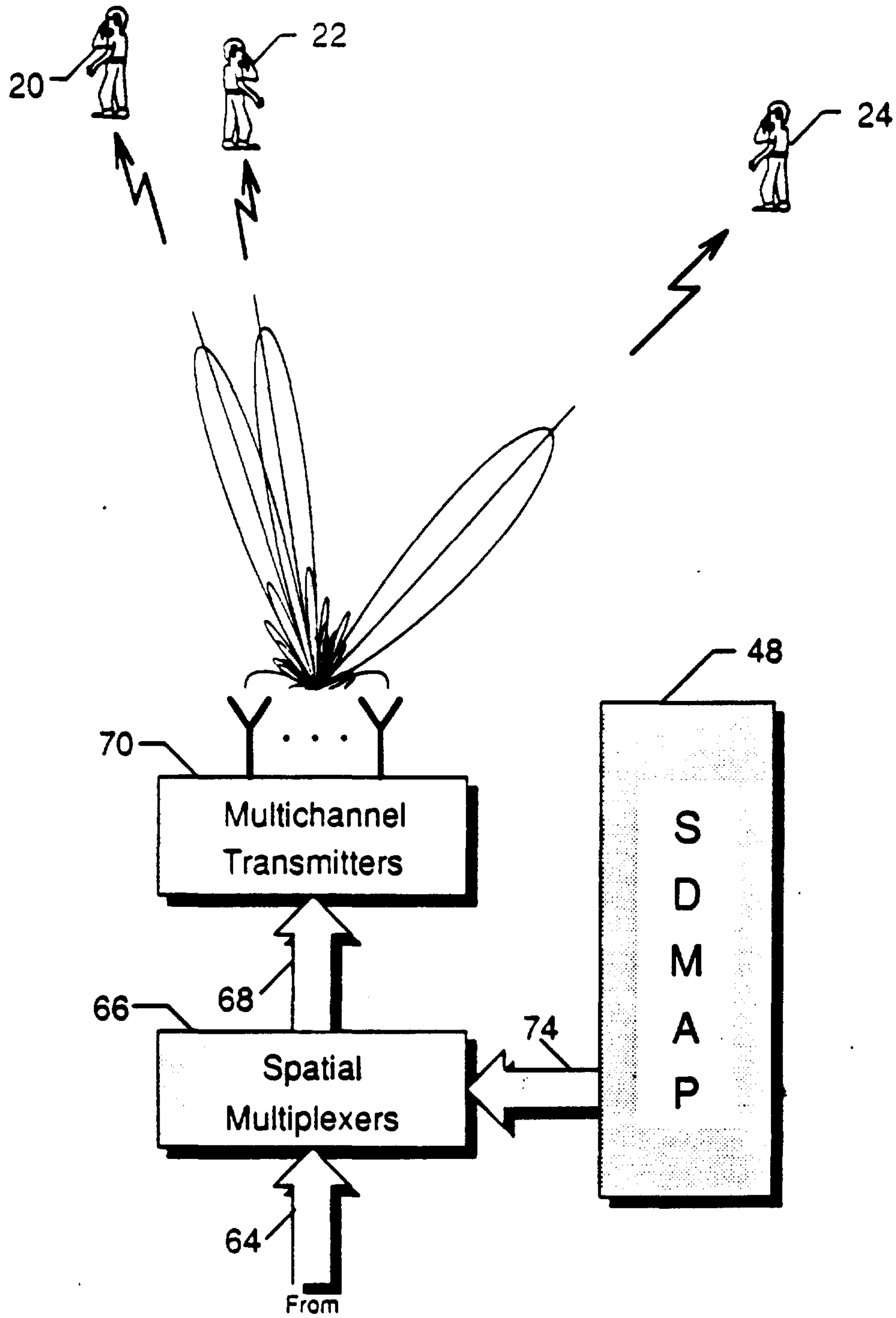

Figure 3-5: Multiple Cochannel Signal Transmission from a Base Station Using SDMA

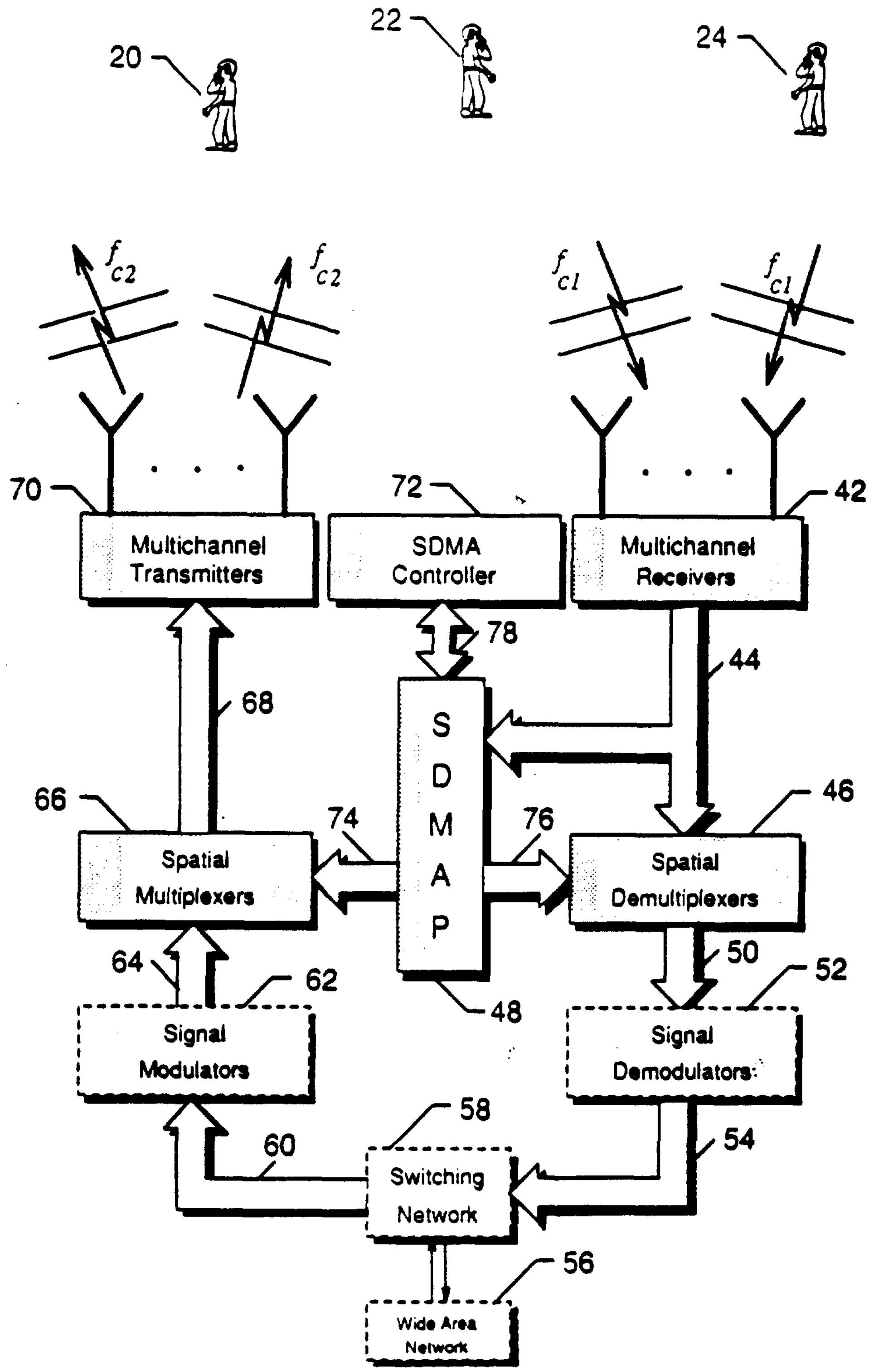

Figure 3-6: Block Diagram of the SDMA System Receiving and Transmitting Multiple Signals in A Single Channel

the receiver consists of a bank of bandpass filters, one such filter tuned to each of the frequency channels assigned to that base station. One such receiver can be assigned to each antenna as shown in FIG. 3-7 (102,104,106), or several antennas can be switched via a high-speed switching circuit to a single receiver. The outputs of the multichannel receivers for a particular (frequency) channel are multiple signals (112,114,116), one signal from that channel for each antenna/receiver pair. These signals are processed as a group by the SDMAP/Spatial Demultiplexer (120) so as to recover the original transmitted signals (122,124,126). Though the diagram implies that a single SDMAP and spatial demultiplexer is dedicated to each channel, several channels can be multiplexed onto a single SDMAP and spatial demodulator depending on processor speed.

Referring back to FIG. 3-6, receiver outputs (44) are digitized after down-conversion to baseband in the multichannel receivers (42) and transmitted in digital form to SDMAPs (48) and spatial multiplexers (46). The outputs of the spatial demultiplexers (50) are demodulated then sent to the switching network (58).

Generally, a function of the SDMAP (48) is to calculate appropriate control signals for the spatial demultiplexer (46) and spatial multiplexer (66) by processing the information received from the receivers (42) and information provided by the SDMA controller (78). The SDMAP also sends tracking and other signal parameter information to the SDMA controller (72) for use in channel assignment and intelligent hand-off. These processes are performed using state-of-the-art signal processing software which implement, among others, recently developed high-resolution direction finding, signal copy, and robust transmission algorithms which are the proprietary property of Spatial Communications, Inc. A detailed description of the SDMAP is given below.

3.2.3.1 Multichannel Receivers

Spatial demultiplexers (46 in FIG. 3-6) demultiplex the outputs (44) of the multichannel receivers (42). This function is performed for each (frequency) receive channel assigned to the base station. In each channel, the signals (44) are appropriately combined by the spatial demultiplexer to provide one output for each signal present in that channel (C1 in FIG. 3-7). Herein, *appropriately combined* means combined so that the signal from each wireless unit in a channel appears at the appropriate output of the spatial demultiplexer. This is possible because to each wireless unit, electromagnetic propagation and reception effectively assigns a unique *spatial code*, and the SDMAP is the spatial ***decoder***. The outputs (50) of the spatial demultiplexer (46 in FIG. 3-6) for a particular channel are the separated signals transmitted from the wireless units to the base station in that channel, and are demodulated as is done currently are then routed through a switching network (58) to their appropriate destination. Signals destined for the wireless units are

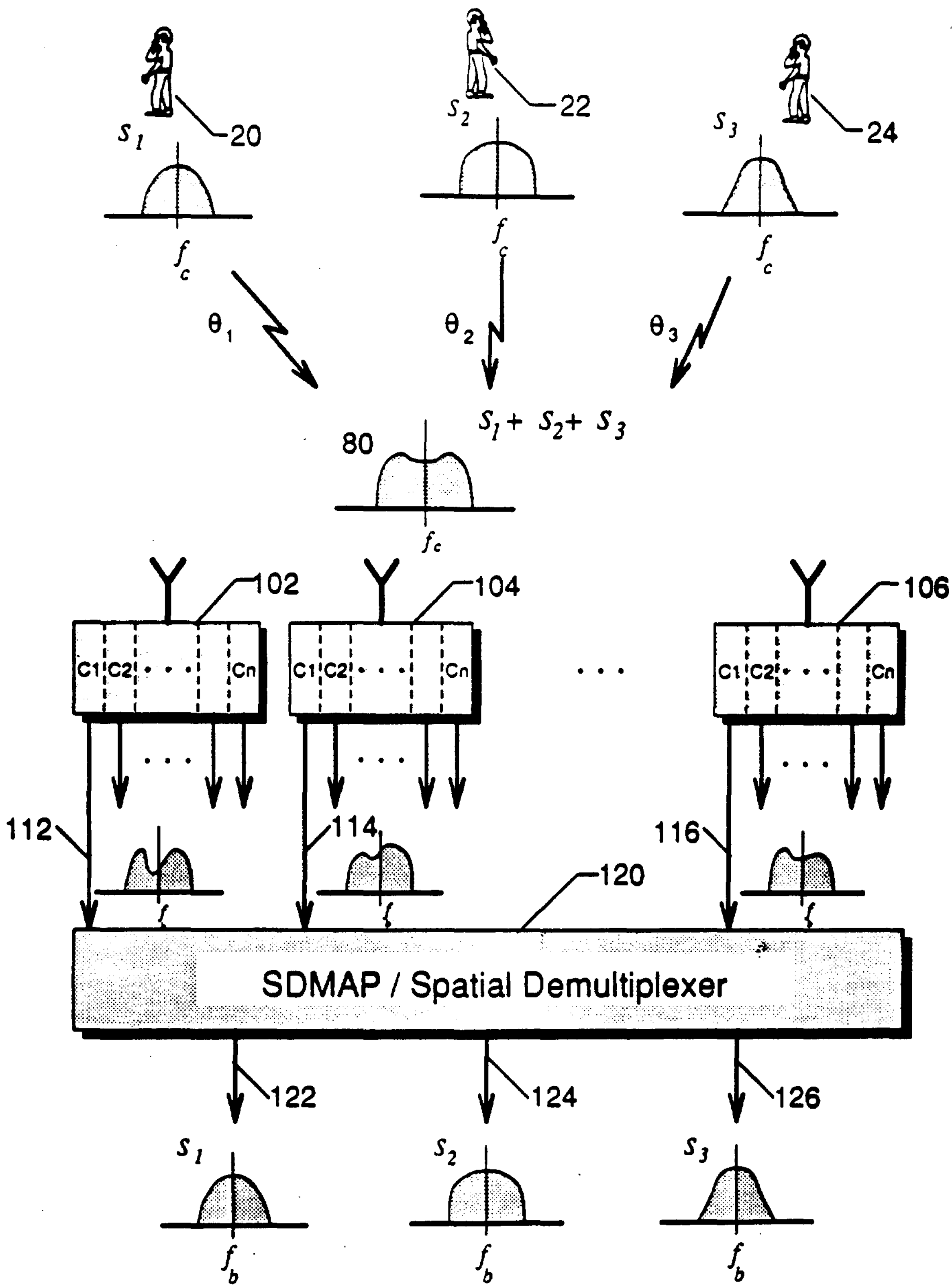

Figure 3-7: Breakdown of the SDMA Multi-Channel Base Station Receiver

obtained from the same switching network (58) and directed to signal modulators (62). Modulated baseband signals (64) are sent to spatial multiplexers (66) where they are appropriately processed as directed by the SDMAP (48) for transmission to the wireless units. In this illustration (FIG. 3-6), these wireless units are assumed to be the same as those whose signals were received in the receivers (42).

3.2.3.2 Multichannel Transmitters

Multichannel transmitters (70) similar in structure to the receivers (42) are employed, there being one transmitter for each of the m_{t_x} transmitting antennas as shown in FIG. 3-8 (152,154,156). Each transmitter appropriately combines the outputs of each channel assigned to the base station for the purpose of transmission of the signals through the associated antenna to the wireless units.

The function of the spatial multiplexer (66) shown in FIG. 3-8 is to multiplex one or more signals (64) into a particular channel (C1 in FIG. 3-8), but *different* spatial channels. The spatial multiplexer (66) appropriately combines the signals (64) and provides one output for the particular channel (C1 in FIG. 3-8) in each transmitter (40). Herein, *appropriately combined* means combined so that each wireless unit receives only the signal intended for it. No other signals arrive at that particular wireless unit receiving in that (frequency) channel. This is a unique aspect of SDMA.

Spatial multiplexing is performed for each channel (C1, C2, ..., Cn in FIG. 3-8). A separate spatial multiplexer can be used for each channel, or the multiplexing task for several channels can be performed by the same multiplexer hardware. The signals (62) are digitized if necessary, appropriately combined in the spatial multiplexer, then sent to the transmitters for D/A conversion and transmission to the wireless units.

3.2.3.3 The Spatial Division Multiple Access Signal Processor (SDMAP)

FIG. 3-9 shows a breakdown of a Spatial Division Multiple Access signal Processor (SDMAP) (48). The function of the SDMAP includes determining how many signals are present in a particular channel, estimating signal parameters such as the spatial location of the transmitters (*i.e.*, directions-of-arrival DOAs and distance from the base station), and determining the appropriate spatial demultiplexing and multiplexing schemes. Inputs (44) to the SDMAP include outputs of base station receivers, one for each receiving antenna. The receivers perform *quadrature detection* of the signals, providing *in-phase* (I) and *quadrature* (Q) components (signals) output from each channel behind each antenna. The receivers can digitize the data before passing it to the SDMAP, or digitization can be performed in the data compressor (160) as aforementioned.

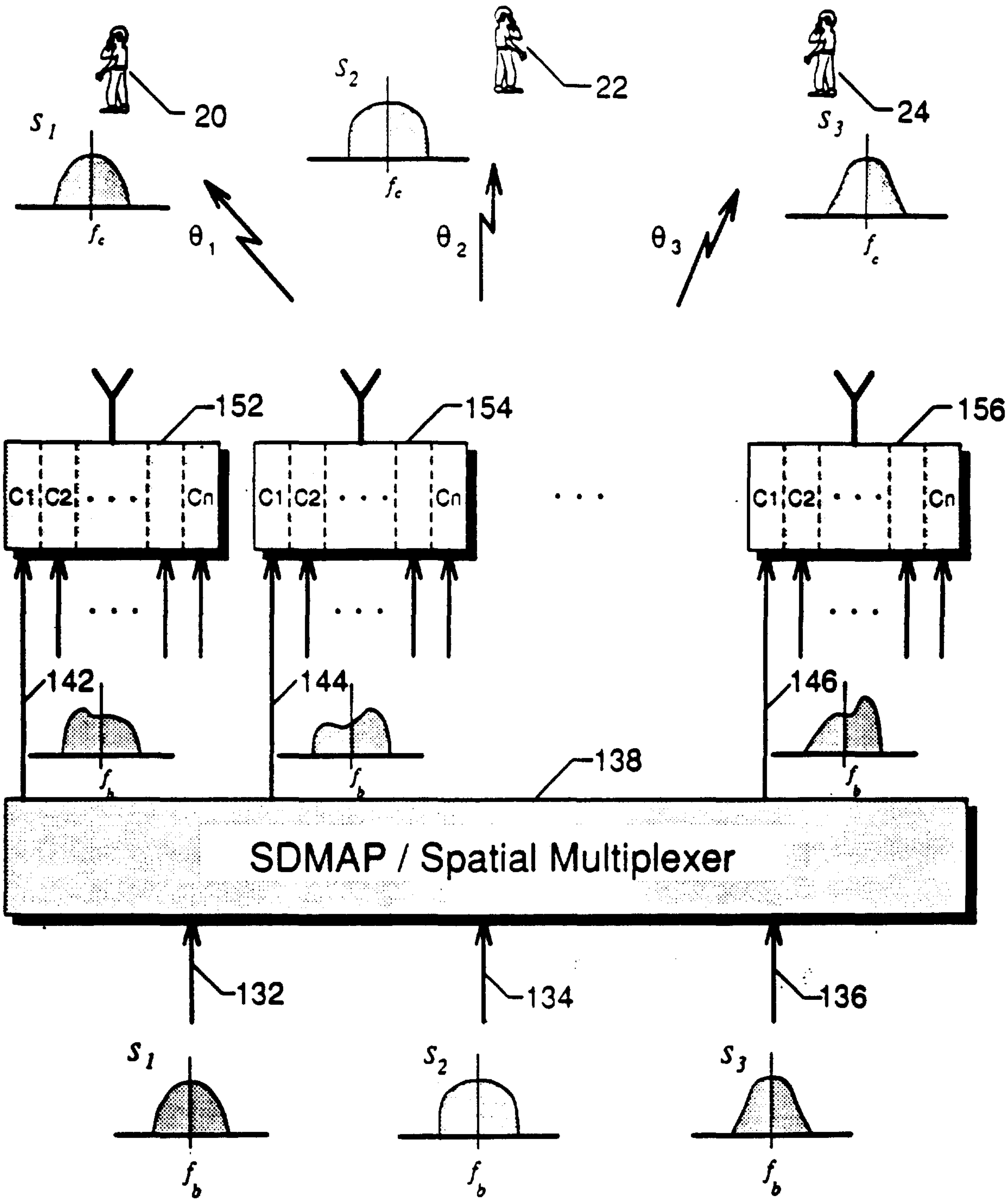

Figure 3-8: Breakdown of the SDMA Multi-Channel Base Station Transmitter

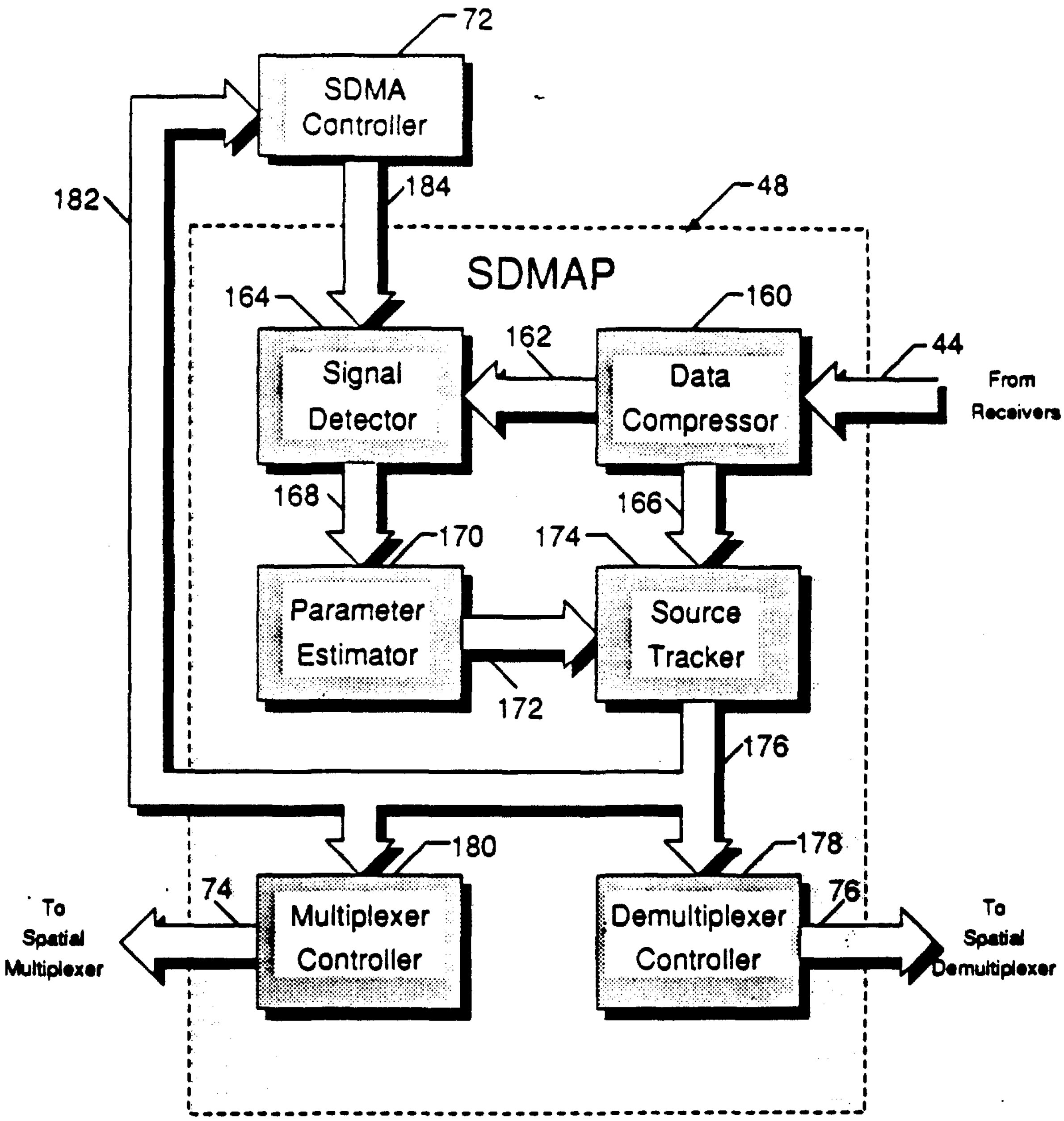

Figure 3-9: Breakdown of the Spatial Division Multiple Access Signal Processor (SDMAP)

In relatively clean RF environments, the SDMAP accomplishes its task by first obtaining estimates of important signal related parameters such as their directions-of-arrival (DOAs) without exploiting temporal properties of the signal. In more complex RF environments such as building interiors, the known training sequences placed in the digital data streams for the purpose of channel equalization are used in conjunction with sensor array information to calculate signal parameter estimates such as DOAs and signal power levels. This information is then used to calculate appropriate *weights* (76) for a spatial demultiplexer implemented as a linear combiner, *i.e.*, a weight-and-sum operation. Time-of-arrival (TOA) related parameters from the parameter estimator are used in conjunction with signal correlation parameters to ascertain which signals are multipath versions of a common signal. Relative delays are then calculated such that the signals can be *coherently combined*, thus further increasing the quality of the estimated signals. The ability to exploit sensor array information in this manner is unique to SDMA.

The function of the spatial demultiplexer can also be performed in conjunction with the estimation of other source parameters such as the DOAs. As an example, the (nearly) constant modulus property (*i.e.*, constant amplitude) of various communication signals such as digital phase-shift-keyed (PSK) and analog FM waveforms can be exploited along with properties of the array of receiving antennas to simultaneously estimate the source waveforms as well as their DOAs. Here, the function of the spatial demultiplexer (46) is assumed in the SDMAP (48), and the outputs of the SDMAP (76) are the spatially demultiplexed signals to be sent to the demodulators.

Referring again to FIG. 3-9, data compression (160) is performed to reduce the amount of data, and can consist of accumulation of a sample covariance matrix involving sums of outer products of the sampled receiver outputs in a particular channel. Hereafter, these sampled outputs are referred to as *data vectors*, and there is one such data vector at each sample time for each of the channels assigned to a particular base station. The compressed data can also be simply the unprocessed data vectors. If I and Q signals (44) are output from the receivers, each data vector is a collection of m_r complex numbers, one for each of the m_r receiver/antenna pairs.

Compressed data (162) are passed to a signal detector (164) for detection of the number of signals present in the channel. Statistical detection schemes are employed in conjunction with information from a SDMA controller (72) to estimate the number of sources present in the channel in this time interval. This information and the (compressed) data (168) are sent to a parameter estimator (170) where estimates of signal parameters including those related to the source locations (*e.g.*, DOAs and range) are obtained.

In simple RF environments, location-related parameter estimates (172) are passed to a source tracker (174). The function of the source tracker is to keep track of the positions of each of the transmitters as a function of time. This is implemented by state-of-the-art nonlinear filtering techniques such as extended Kalman filters (EKFs). Inputs to the EKF embodiment include the DOAs and TOAs from the local base station. DOA and TOA measurements from other nearby cell sites also receiving transmissions from the mobile units can be incorporated as well along with known locations of the base stations to further improve the estimation accuracy of the EKF. The tracker (174) outputs are sent along with the (compressed) data (176) to a spatial demultiplexer controller (178), to control the function of the spatial demultiplexer, and to a spatial multiplexer controller (180) to control the function of the spatial multiplexer.

3.2.4 The SDMA Controller

FIG. 3-10 displays a SDMA controller (72) which supervises channel allocation, and a plurality of SDMA systems (202,204,206). As aforementioned, each SDMA system receives signals (44a,44b,44c) from the multichannel receivers (42) and sends signals (68a,68b,68c) to the multichannel transmitters (70) for transmission to the wireless units. The SDMA systems also communicate (tracking) information (182a,182b,182c) as aforementioned to the SDMA controller and receive information (182a,182b,182c) from the SDMA controller. Not shown in this illustration is the link between the base stations and their access to the wide area network through a switching network.

The function of the SDMA system is performed for each channel (202,204,206), denoted CH 1, CH 2, ..., CH n in FIG. 3-10, allocated to a base station for reception. There can be a separate SDMA system for each channel, or several channels can be processed in the same SDMA system depending on system load and processor speed.

An objective of the SDMA controller (72) is to prevent wireless units from becoming coincident in (frequency or code) channel, time, and spatial (location) space. As required, the controller instructs the wireless units to change to different (frequency or code) channels via standard messaging schemes.

SDMA controllers at various base stations (190,194,200) can also send tracking and frequency allocation information, in addition to other relevant source parameters such as signal power, concerning all the wireless units in their cell (192,196,198) to a base station supervisor (220). This information can be used to simplify hand-off procedures employed in current systems. With knowledge of the locations and velocities of all the transmitters and knowledge of the areas covered by each of the base stations, efficient and reliable hand-off strategies can be implemented.

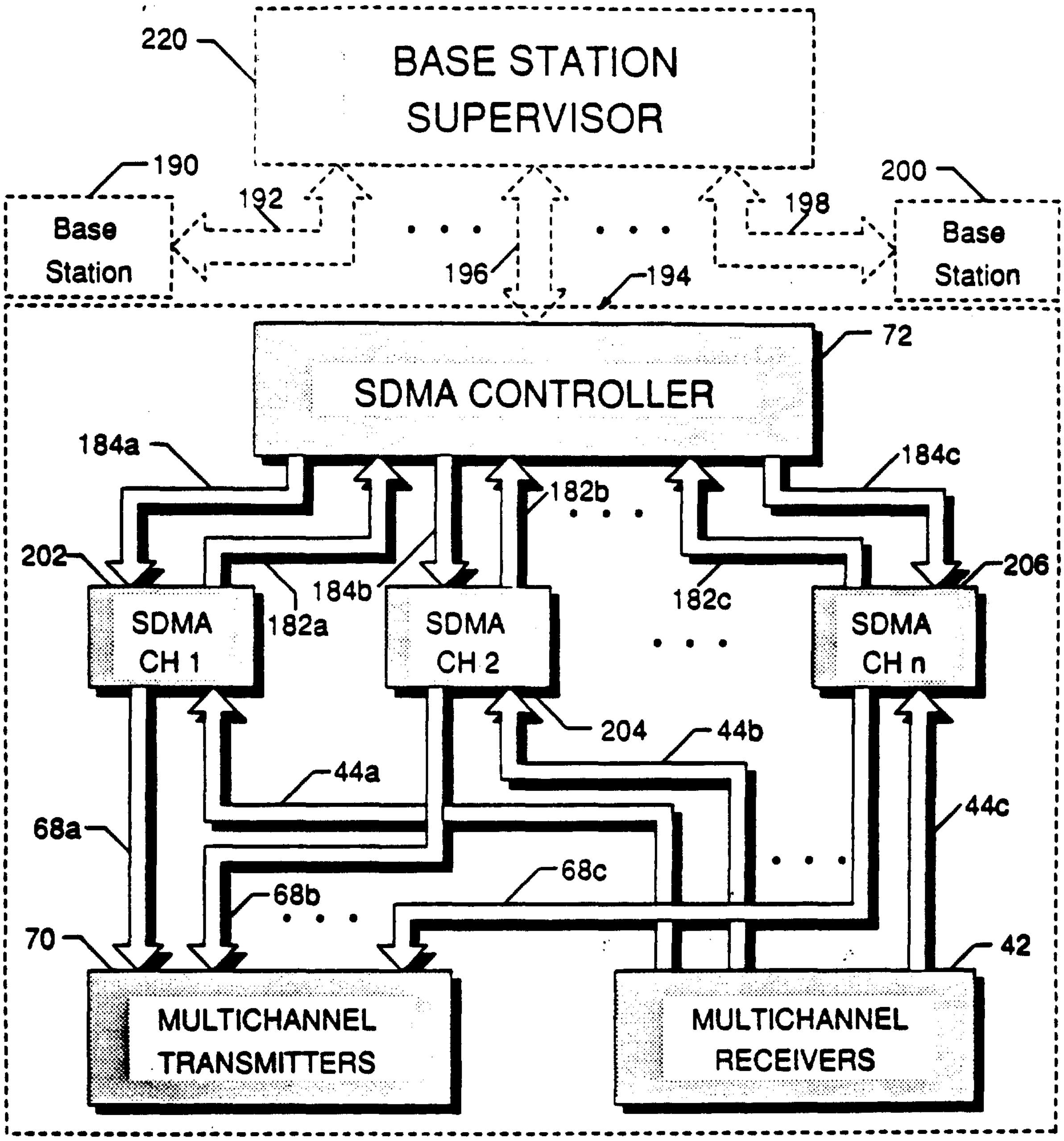

Figure 3-10: Breakdown of Multiple SDMA Processors Increasing Base Station Capacity

The function of the SDMA controller can also include relaying to each base station the locations and channel assignments of transmitters in neighboring cells. This information can be used in the spatial multiplexer and demultiplexer controllers in the SDMAP to improve the performance of the spatial multiplexers and demultiplexers. Further improvements in capacity are also realized herein by allowing dynamic allocation of receive and transmit channels among the various cell sites and mobile units. The ability to track multiple transmitters in wireless communication networks and the significant improvements made with regard to system capacity and quality are unique to SDMA.

4. Benefits of SDMA

SDMA addresses the key issues and problems facing the PCS industry as well as other wireless communication networks by essentially restoring the property of wireline service, that of point-to-point communication, lost when wires are eliminated in favor of wide-area (omnidirectional) transmission and reception of (electromagnetic) radiation. No attempt is made in current systems to:

1. exploit information collected by an array of sensors for the purpose of detecting and estimating the location of multiple signals on the same (frequency) channel at the same time,

2. simultaneously estimate all transmitted signals, or

3. use spatial information to simultaneously selectively transmit different signals to one or more users on the same (frequency) channel.

These are unique to SDMA and can significantly improve the capacity and quality of PCSs. As discussed in detail in Section 6, the cost associated with this improvement is the increase in hardware complexity per base station required. The overall system costs per user can be reduced, however, since more users are allowed, and fewer base stations are required.

The benefits of SDMA include:

1. allowing simultaneous use of any conventional (frequency, time-slot, or code) channel by multiple users, none of which occupy the same location in space, thereby increasing the capacity (*i.e., spectral efficiency*) of current PCS wireless information networks,

2. tracking of mobile sources, mitigating hand-off and signal mangement problems present inherent in current mobile cellular communication systems,

3. transmitter position determination, enabling location-related services to be provided,

4. independence of the particular signal modulation type and therefore compatibility with current and future modulation schemes in wireless communication systems,

5. improved signal quality at both transmitters and receivers,

6. a certain amount of communication security by transmitting signals only in preferred directions thereby limiting the amount of unintentional radiation,

7. allowing a decrease in transmitter power to be effected at the base station by directive transmission while still improving signal quality by increasing amount of power received by the mobile unit,

8. decrease in signal degradation due to cochannel interference thereby allowing frequencies in adjacent cells to be re-used more frequently, further increasing system capacity,

9. providing capability for the new PCS systems to coexist with other primary users of the same bands (*e.g.*, point-to-point microwave) without having to require modifications of any of the other existing system operations.

In the case of FDMA/TDMA systems similar to the proposed IS-54 digital cellular system, the increase in spectral efficiency is effected by allowing multiple users to occupy the same frequency channels and the same time slot as long as they are not at the same location (angular position) relative to the local base station. The number of such simultaneous users is theoretically limited to the number of elements in the receive array less one, however practically for robustness considerations the number should be limited to on the order of 50% to 70% of the number of elements. Thus, a six element receive array of omni-directional antennas can practically track four (4) mobile transmitters providing a factor of four (4) increase in capacity. As aforementioned, further increases in spectral efficiency can be realized by increasing the number of antennas. A practical upper limit of approximately a factor of ten (10) over omnidirectional base stations is anticipated given the present state of DSP technology and the complexity of the RF environments to be encountered. In summary, increases in spectral efficiency of factors from 2 to 10, dependent upon the system parameters required, are achievable in the present state-of-the-art for FDMA/TDMA systems. Base stations can be designed to meet expected demand while minimizing hardware costs by designing with the appropriate number of antennas. When necessary, the spectral efficiency can be increased (up to a factor of 10) by adding more antennas. Though the technical approach is different, similar capacity increases can be realized for CDMA systems where many users share the same frequency band, but use different *temporal codes*.

The ability to establish full-duplex links requires the transmit array have at least as many elements as cochannel mobile units. Practically, as mentioned previously, 50% to 100% more antennas than mobile units provides a degree of robustness to system errors and is recommended. When appropriately placed, more transmit antennas can be used to further reduce power consumption and RF pollution by confining the transmitted energy to smaller angular sectors. Mathematically, the power transmitted in each of M_{tx} transmit antennas can be reduced be a factor of M_{tx}^2 yielding an overall power reduction of a factor of M_{tx} while delivering the same amount of power to the mobile units.

The ability to directionally transmit can also be used to increase the effective coverage area of each cell, trading total transmitter power for cell radius. Thus, if the total transmitter power is held constant and a 1/3-power law is assumed for RF attenuation, the cell radius can be increased by $M^{1/3}$ leading to the requirement for fewer base stations.

An important benefit of SDMA implementation in the PCS environment is the ability to coexist with current users of the proposed PCS spectrum (901-9600 MHz, 1800-2200 MHz). There are a significant number of microwave users currently occupying at least one of the bands (*i.e.*, 1850-1990 MHz) proposed for the next generation PCS. The cost of relocation of these users could be substantial. With SDMA, it is possible for established microwave users to coexist with the new PCS users with extremely small *exclusion zones* since the PCS system can be designed (base stations appropriately located) so that complete area coverage is provided without illuminating the microwave antennas (thereby interfering with the current users) from the base stations. Furthermore, since the PCS handsets can operate at lower power than without SDMA, they will contribute proportionately less RF *pollution*.

The ability of the SDMA system to locate and track transmitters also provides several immediate benefits. This ability can be directly used to mitigate the problems associated with cellular-type communication systems when users move from cell to cell. Without knowledge of the relative location of the transmitter, assigning of the transmitter to the appropriate base station becomes a problem. However, when the location of the transmitter is known, assignment is a trivial task. Furthermore, knowledge of the transmitter location enables PCS operators to provide a host of position-related services which other proposed systems can not provide. A unique and valuable element of security (being able to locate a child in distress, *etc.*.) is also provided when the transmitter location is known.

All of these benefits of the SDMA system accrue from the use of smart antennas and proprietary signal processing technology. The ability to locate, track, spatially demultiplex, and spatially multiplex signals to and from multiple users results in a significant increase in spectral efficiency not currently achievable by any other system. The compatibility of SDMA with current modulation schemes, and its inherent ability to handle increasing demand (modularity) make it ideal for PCS implementation.

5. Status of SDMA

SDMA technology is a blend of phased-array antenna technology which has been used successfully over the last 40 years in many military applications, proprietary signal processing techniques developed over the last 15 years by principals of Spatial Communications, Inc., and state-of-the-art digital signal processing (DSP) hardware to implement these algorithms in real-time. As such, there is little technical risk involved in implementing SDMA. The critical components of the SDMA system include:

1. antenna arrays and RF frontends,
2. proprietary SDMA signal processing algorithms,
3. DSP hardware to implement these algorithms in real-time,
4. interface equipment to existing base stations.

Of these components, only the interface equipment is still under development. Such interfaces will be designed into the prototype system to be tested within the next year. Since the antenna arrays required are collections of simple antennas currently employed, there is no development required. The proprietary SDMA signal processing algorithms have been coded and tested and are currently available. The demonstrations completed to date involve simulating the RF environment and the antenna arrays. Experimentation is continuing in the UHF band at 900 MHz and at 1.9 GHz to demonstrate the ability of SDMA to successfully track and demodulate cochannel emitters in a controlled RF environment. A working demonstration of the full-duplex SDMA system is expected by the end of summer 1992.

5.1 Computer Simulations

In this section, the results of computer simulations indicating the performance of the SDMA system in its ability to increase capacity and quality in PCSs is presented. The computer model of the RF environment used models two of the dominant effects in urban and rural environments. The first is scattering of the RF energy from nearby structures such as buildings, and results in *Rayleigh fading*. This phenomenon can be viewed essentially as a time-varying antenna gain as seen at the base station where the bandwidth of the temporal variation is directly related to the velocity of the transmitter relative the local scatterers measured in wavelengths per second. For pedestrians, this is not expected to be in excess of 100 Hz and will generally be much less. The second effect is specular multipath with significant delays with respect to the underlying signal bandwidth. This phenomenon can be significant in large urban centers with many tall structures, and in certain geographical areas such as Salt Lake City, Utah where mountainous terrain borders metropolitan centers.

In the first simulation, analog FM handsets (at 1920 MHz) are employed, and it is assumed that the RF environment is similar to that representative of an urban or suburban area in which local scattering effects (within a radius of approximately 100λ) dominate. It is further assumed that the base station is not situated in close proximity (within approximately 10λ) to any (electromagnetic) reflecting structures.

FIG. 5-1 illustrates the capability of SDMA to simultaneously track two transmitters in the same channel, and to spatially demultiplex the received signals to estimate the transmitted waveforms individually. The receiving array is composed of a 10-element uniform linear array of elements spaced one half-wavelength apart, *i.e.*, 7.8 cm at 1920 MHz. The two FM transmitters are moving toward each other and actually cross paths, *i.e.*, the DOAs are at one point during the interval the same. A severe Rayleigh fading environment is simulated with a fade rate in excess of 100 Hz. The receiver outputs are processed in blocks of 400 data vectors (0.05 sec of data sampled at 8 KHz). In spite of the fact that the transmitters are less than $2°$ apart at 1.7 sec, approximately 30 m separation 1 km from the base station, the individual signal waveforms are accurately reconstructed as shown in the lower illustration. This figure clearly manifests the efficacy of the SDMA system as such performance has not been achieved previously. The ability to separate cochannel sources in close proximity to one another and to successfully spatially demultiplex the received signals is unique to SDMA.

FIG. 5-2 is a continuation of FIG. 5-1 illustrating the capability to simultaneously track multiple transmitters in the same channel where the trajectories cross. At the midpoint of the estimation interval, the transmitters are at the same DOA. As is easily seen, the SDMA system tracks the DOAs of the transmitters successfully. The ability to track intersecting trajectories of cochannel transmitters from DOA measurements made by an array of sensors is unique to SDMA.

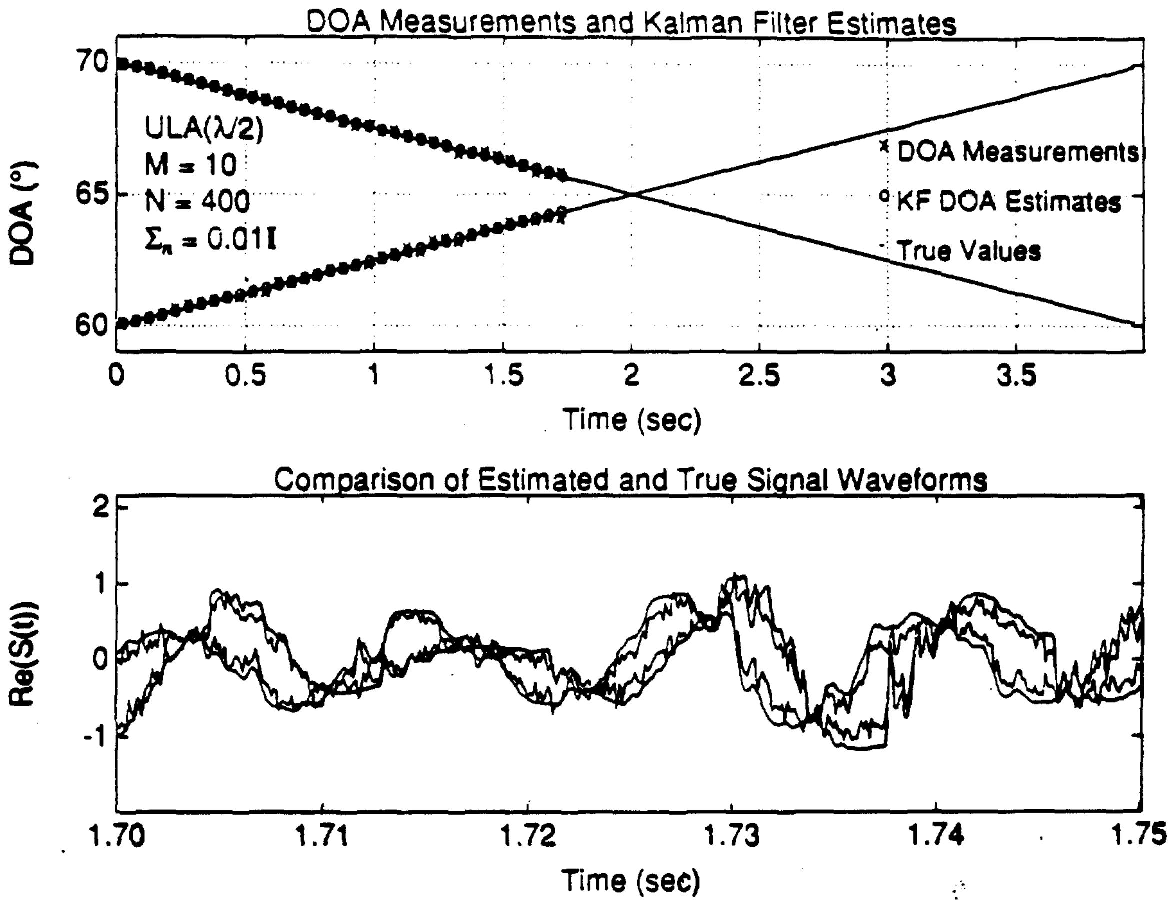

Figure 5-1: Simulated SDMA Processor Outputs — DOA Tracking and Signal Copy of Closely Spaced Moving FM Transmitters in a Severe Rayleigh Fading Environment

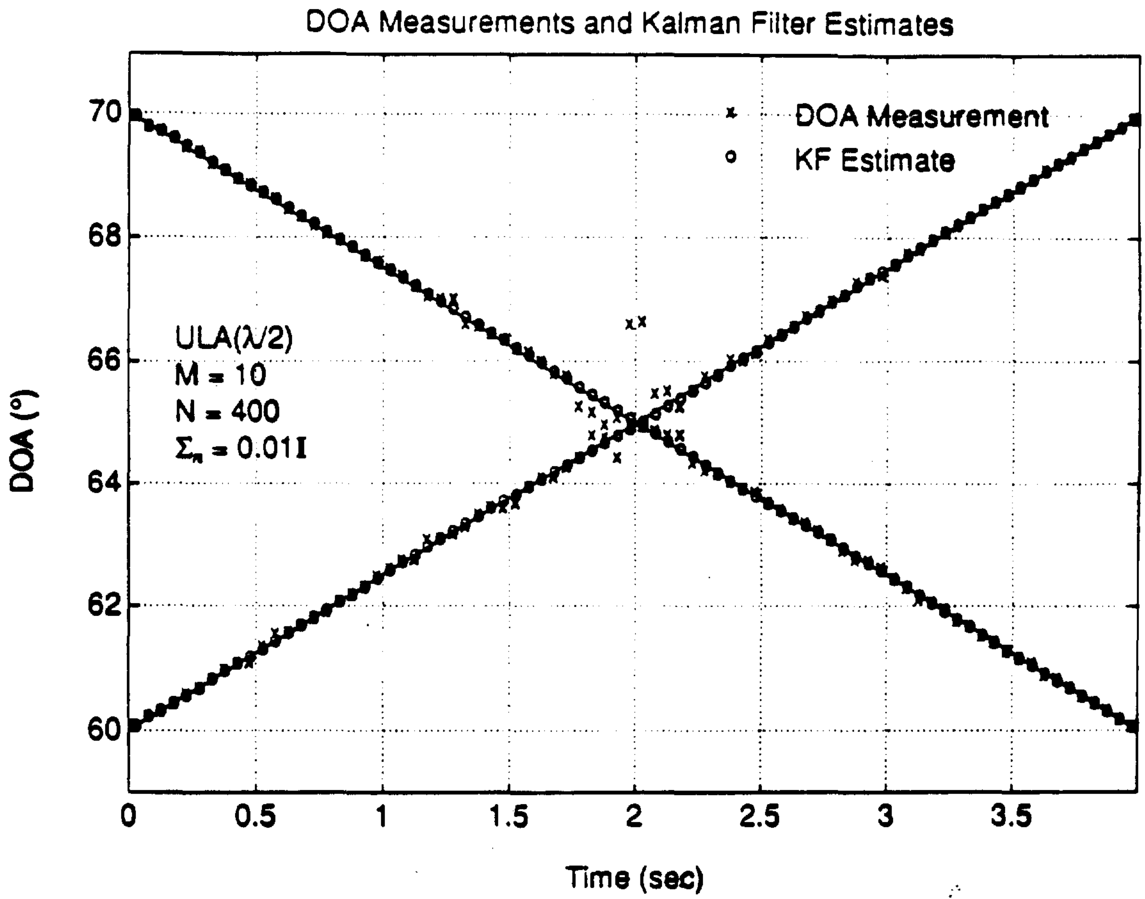

Figure 5-2: Simulated SDMA Tracker Outputs — DOA Estimates and Kalman Filter Tracking of FM Transmitters Crossing Tracks in a Severe Rayleigh Fading Environment